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WHY INITIAL CONDITIONS ARE IMPORTANT

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ABSTRACT

Most simulation textbooks assume that a model can be started in an empty state and the final output will not be affected, so long as the "warm-up period" is excluded from the analysis. In this paper we test this assumption, using a discrete-event model of a existing manufacturing facility. Using a series of model runs with no initial Work in Progress (WIP) and another series of simulation runs with a realistic initial level of WIP, the results can be compared and contrasted. While the results show similar shaped profiles in terms of throughput and lead time, the differences between the curves has important practical implications.

1 INTRODUCTION

Many textbooks on simulation modeling, Law and Kelton (1991) or Kleijnen (1986), describe the process of building and validating a simulation model. Much emphasis is placed on the development of a credible model and the subsequent analysis of stochastic results. While this emphasis does not seem out of order for many of the problems being investigated, what appears to be lacking is a better understanding the initial conditions have on the overall results. We were struck by this, as it was difficult to build a credible model of the facility we were studying without including the initial levels of Work In Progress (WIP) in the model. Given this, the aim of this paper is to compare and contrast the differences between the simulation model when it is run with and without the initial WIP levels.

The facility under investigation was a typical batch manufacturing plant, laid out along functional lines, with very little streamlining of operations, as described previously, see Gunn and Nahavandi (2000, 2002). A large product range and the plant layout meant the operational characteristics lie somewhere between job shop batch manufacturing and high volume repetitive manufacturing. Goods are typically transferred between operations via metal buckets, through the use of cranes and forklifts. In order to study the problem for this factory, a schedule was extracted from the company databases, containing over 4000 work orders. The factory was characterised by high levels of WIP and long production lead times. As pointed out in other studies, such as Goldratt (1986), this is indicative of a factory that needs better control over the release of product onto the shop floor. This is in essence the aim of our work, to reduce WIP and production lead times, without adversely affecting production throughput.

Hopp and Spearman (1996) have provided the base analysis of the relationship between WIP, throughput and lead times. Using a perfectly balanced transfer line, containing four machines with buffers in front of each, their case study investigates the throughput and lead time along the line as the level of WIP is increased. Such work has been also studied by Andijani (1997). The result of their simplified analysis suggests that a point exists within a manufacturing line or plant where the throughput is at or near a maximum, whilst the lead time is at or near a minimum. In previous work, Gunn and Nahavandi (2000), we have suggested this is the optimum WIP level. While the analysis is for a highly idealized case, the result introduces the idea of an optimum WIP level, which will used in later sections of this paper.

2 FACTORY INVESTIGATION

As described in the introduction, the factory under investigation was a typical batch manufacturing facility. A discrete–event simulation model was developed that incorporated all the six hundred work-centers spread across several sites. Of these work-centers, just over two hundred were routed on a regular basis. As the factory was a typical batch and queue arrangement, there was no fixed routing for each specific product. A generalized system of product routing was developed within the model and controlled through the schedule file. Thus the schedule file controlled not only the work order release into the simulated shop floor, but also contained a sequence of numbers representing a product routing after the primary work-center. These numbers represented the series of machines that the particular work order was to pass through, from which the routing system directed the buckets in the work orders to the correct simulated work-center. In this manner the routings for the same products could be, and were, altered at work order release time. The same products made several months apart could therefore be routed through different machines depending upon availability and quality requirements.

The model was validated against factory data, using a series of transactions from the company databases, as well as audits performed on the factory floor as to the veracity of the data. Much information was collected from production logs, which are essentially hand written, and used to verify the data against the transaction files. Two steps for building a credible model were considered important. Firstly to verify that the model ran to completion for all of the work orders in the schedule file, apart from some of the later work orders which will still exist as virtual WIP at the end of the simulation run. This was achieved by comparing the numbers of work orders started and completed as a function of both time, and primary work-center.

The second requirement for validation was to compare the output of the model matched the factory information. This was achieved by tuning the various production parameters such as production rates and lead times across key work-centers. In essence, since we were looking at an optimum WIP problem, both the throughput and lead times needed to match the reality of the factory. This was performed to an acceptable degree.

3 EXPERIMENTAL DESIGN – CONSTANT WORK IN PROGRESS

A series of experiments have been designed to examine a scenario suggested in Hopp and Spearmann (1996), where the level of WIP is maintained at a constant value, called the CONWIP (for Constant WIP) case. In this scenario, the level of WIP is capped at a maximum value and not allowed to increase beyond this point. With regards to the simulation, this cap takes the form of a variable, which places a limit on the total number of buckets on the simulated shop floor, and can be altered at run time through a text file.

The basic experimental design involves starting with a high level of maximum WIP, and reducing this by 200 buckets for each simulation run. At the end of each simulation, the results are calculated via a user-defined macro, as shown in Figure 1, before the next simulation performed. At the end of all simulation runs, at some user-defined minimum level of CONWIP, the results can be plotted as graphs showing the throughput and lead time against WIP level. Two sets of simulation runs will be performed; one set with a schedule file containing no initial inventory or WIP, and one containing a good representation of the WIP level just prior to the schedule start date.

Using the company databases, the initial WIP level could be easily determined by a simple methodology. A list of work orders was developed that were started in the two-month period prior to the start date of the schedule file used for validating the model. From these work orders, it was determined which work orders were completed or partially completed within that two month time period, leaving many items that were still outstanding at the start date of the simulation schedule. The work orders, or part work orders, that were still outstanding therefore become the initial WIP work orders existing within the factory. The exact location and quantity of each of the work orders could also be determined from the last transaction in the transaction database, and knowledge of the next step in the routing. The simulation schedule file was expanded to include the initial WIP at each of the work-centers downstream of the initial machines. The simulation logic was then altered to model and place the buckets from each of the work orders on the correct input buffer for each of the downstream machines. While not all the initial WIP was recorded by this methodology (Some partial work orders were present that were over two months old), by starting the model with a prescribed initial condition a realistic representation the initial state of the plant is achieved.

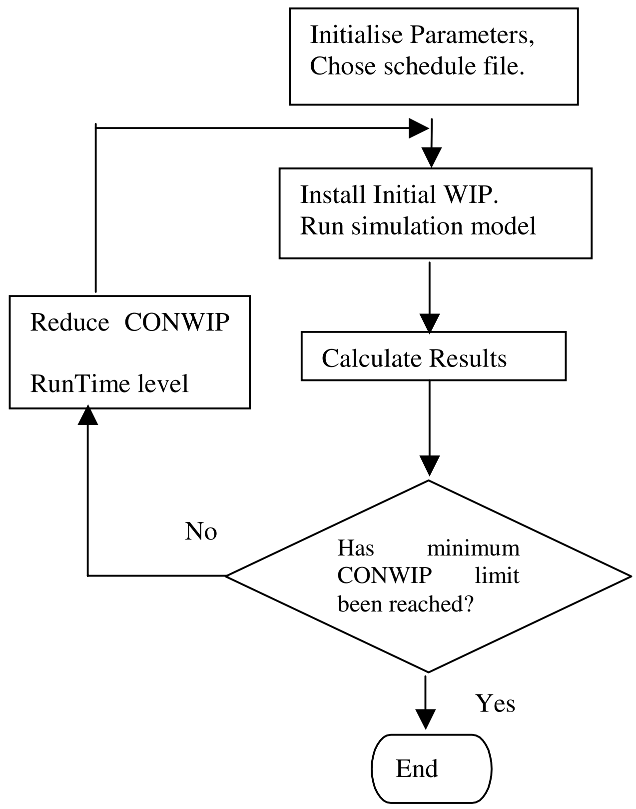

Figure 1: Initial Inventory and CONWIP Experimental Design

4 RESULTS

A deterministic model has been developed to highlight the basis of the analysis. This simplifies the analysis substantially, in that we were interested in the base behaviour of a complex system. While the experiment from Hopp and Spearmann (1996) was a good starting point, what we wanted to investigate was whether this occurred in practice. Using a deterministic model proved the quickest way to achieve this. Caution was used when applying the results, though, as a deterministic model generally understates the lead times and buffer levels required.

Several different sets of results can be obtained from the one set of data. The prime area for confusion is how best to measure throughput and WIP levels. Throughput can be viewed as dollars (cost), mass (tonnes) or pieces (number of product) per unit time. Because different parts of the plant perform at different rates and are controlled via different mechanisms, measuring the throughput, or WIP level, of the plant is not obvious. For example, in the factory that was studied, some parts of the plant are controlled in a kilogram per hour manner, other parts of the plant are controlled in a pieces per hour manner, whilst other areas are controlled in a bucket per hour or day rate. This dichotomy is best solved by examining what matters most to business, the dollar per hour rates, but these numbers are variable, subject to changes from both internal and external factors. In essence all three variables will be examined and conclusions drawn.

Figure 2 provides an overview of the effect modifying the maximum level of WIP on both the production lead time (RHS y-axis) and the pieces throughput (LHS y-axis). Both are measured against the pieces WIP on the x-axis. Both sets of results have been presented on the graph, so that direct comparison can be made between the zero and non-zero initial inventory condition. The zero initial condition case has been plotted as dotted lines (for both lead time and throughput), while the non-zero case has been plotted as solid lines. Also plotted is the level of 95% throughput, which is the cut-off for determining the point of optimum WIP. Throughput of 95% is considered as the best choice, as most production managers would give up some percentage of throughput for greater flexibility in production. This has been included so that direct comparison of the optimum WIP level can be made.

Starting with the initial number of buckets set at 1800, the reduction in WIP can be observed at every point in the throughput and lead time curves. Each diamond (throughput) and square (lead time) is a reduction, of 200 buckets, in the maximum allowable level of WIP in the simulated plant.

While the examination of the dotted lines in Figure 2 have been presented elsewhere, Gunn and Nahavandi (2002), a concise discussion of the graph will be given. As the maximum CONWIP level is reduced, the average level of WIP also reduces. For the case of no-initial WIP, throughput shows only a slight decline up till around 1000 buckets, hovering just above 1 million pieces per day. Average lead time, however, indicates a decrease from highs of around 28 days, down to around 16 days. The throughput does not decrease dramatically, while the lead time decreases sharply at high levels of WIP. Below 15 million pieces in WIP, the throughput begins to decrease at a more rapid pace, while the lead time begins to level out. At this point the factory is past the point of optimum WIP, the point at which the throughput drops below 95% of the maximum throughput.

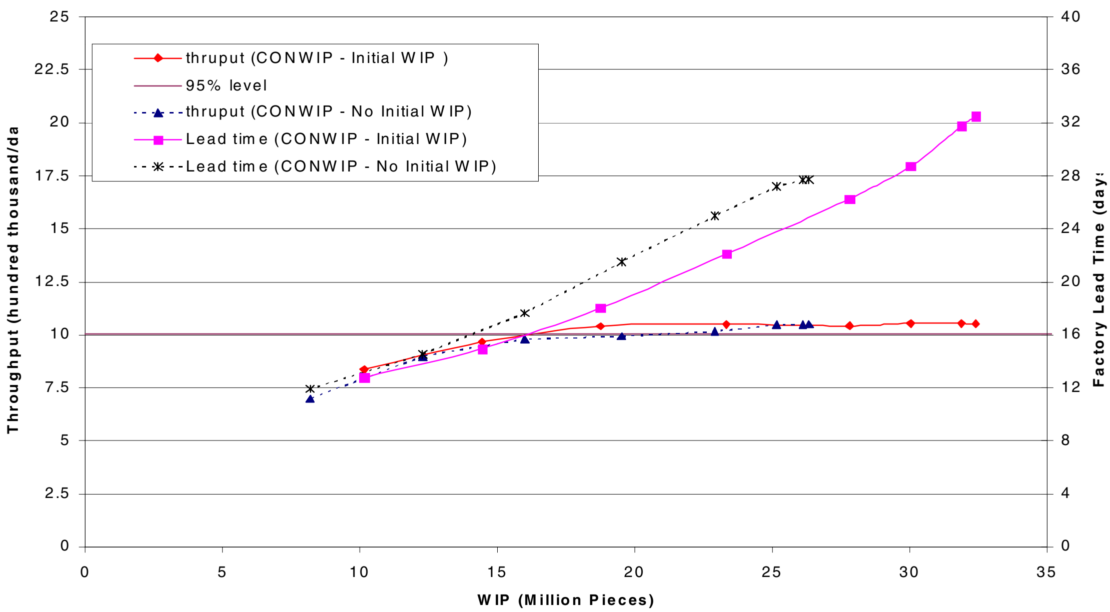

Figure 2: Pieces Throughput and Lead Time Versus Pieces WIP

When the comparison is made with the non-zero initial WIP case in the Figure 2, the differences become obvious. In the case of throughput, the difference between the solid and dotted lines is not the maximum level of throughput (as they are very similar), but the extent of the maximum WIP levels recorded. With initial WIP included in the simulation runs we see an increase from 25million pieces to 33 million pieces for the upper limit of CONWIP (1800 buckets). Further to this, in the case of non-zero initial WIP, very little drop in throughput is observed until around 15 million pieces of WIP, whereas the no initial WIP case drops below the 95% level at around 17.5 million pieces. Not only are the changes in the shape of the curves, but the change in WIP level from maximum to the 95% level is much more significant for the initial WIP case. The lead time curves show significant differences between the two cases, of the order of 2 to 3 days for similar levels of WIP. This is due partially to product mix passing through the key bottleneck workcenters, and the slightly higher throughput. The results of the initial WIP case were much more consistent with the observations in the factory. The measured WIP levels were consistently observed above 30 million pieces, with measured throughput levels similar to the throughputs in the model. Starting with a zero initial inventory condition could never obtain the levels of WIP observed in the factory, even though the throughput rates were about right. This is because the factory never exists in a zero WIP condition. There is always WIP at the start of the model, as this is the existing condition in the factory. Thus, any product passing through the factory will have to wait in the queues before the main bottleneck machines downstream of the primary work-centers. In the case of the zero initial inventory condition, these queues take time to develop, and hence the overall WIP level will be lower.

The above mentioned behavior is reasonably simply described by examining the process flow and bottlenecks within the plant. Basically at low levels of WIP, the first machines in the routing are the bottlenecks to production, as they are continually starved of buckets into which to make product. Hence throughput is low, but the lead times have a natural minimum level as suggested in Hopp and Spearmann (1996). As the level of WIP is increased, then queues begin to develop in front of the downstream work-centers, and the percentage of queue time in the total lead time value increases. When all the key bottleneck resources have significant queues on their input buffers, then the increase in throughput tapers off with increasing WIP, while the lead time begins to increase. A sharp change in rate of change of throughput is not observed in this case. Instead when all the key downstream bottlenecks have significant queues, the throughput can still slowly increase due to product being manufactured but not passing through the key bottlenecks.

Due to the batch nature of the manufacturing facility, the throughput and WIP levels can be described in terms of quantity (i.e. pieces per day) or in terms of mass (i.e. kilograms per day). A graph can be plotted similar to Figure 2, where the throughput and WIP levels are measured in terms of tonnes rather than pieces. Such a graph is presented in Figure 3. Examination of this graph provides some similarities with the previous figure, and some significant differences. Again the maximum level of WIP is increased from 750 tonnes to 950 tonnes for the initial inventory case, which is again consistent with the plant data. The throughput and lead time curves, however, are more closely aligned in this case. Little difference is observed between the lead time curves, and the throughput is slightly lower in the case of initial inventory. The throughput curve provides an interesting case, as it appears to pass through two plateaus, one between 800 and 950 tonnes, and the next between 450 and 550 tonnes, before dropping away at a rapid rate towards zero. This means the optimum WIP level is significantly higher for the initial inventory case, but still a significant saving on the maximum CONWIP case. Overall, the results for the non-zero initial inventory case are consistent with factory data in terms of throughput, WIP and lead time.

The dichotomy of determining whether throughput should be measured in terms of kilograms per day or pieces per day can be resolved by examining what counts most to a business, the value of the product.

Dollar costs are a key factor in the determination of most business decisions. By focussing on dollars this study looks directly at one of the key business drivers. Figure 4 is a similar graph to Figures 2 and 3 but plots the dollar throughput and WIP levels. For the non-zero initial inventory case, he throughput increases passes through two plateaus, similar to Figure 3.

Figure 4 presents a similar picture to Figure 3, in that the differences aren't large between the lead times (less than 1 day) between the initial condition cases. The optimum WIP level is around 2.75 million dollars for the non-zero initial inventory case, which is not significantly different from the zero inventory case. The potential saving in WIP, however, is much higher, as this represents a saving of around 1.4 million dollars in WIP and around 12 days in production lead time. The non-zero initial inventory case represents a significant saving in terms of dollars compared with the non-zero case, and hence makes a large practical difference when "selling" the results of the simulation work, and having the results implemented in practice. The results have essentially been implemented and the savings gained by the company involved.

5 CONCLUSIONS

An optimum level of WIP can be obtained for a "real-world" factory, utilising discrete event simulation modelling. Using a model developed for a batch manufacturer, it has been shown that the factory throughput only drops slowly as the level of WIP is halved, from the initially high

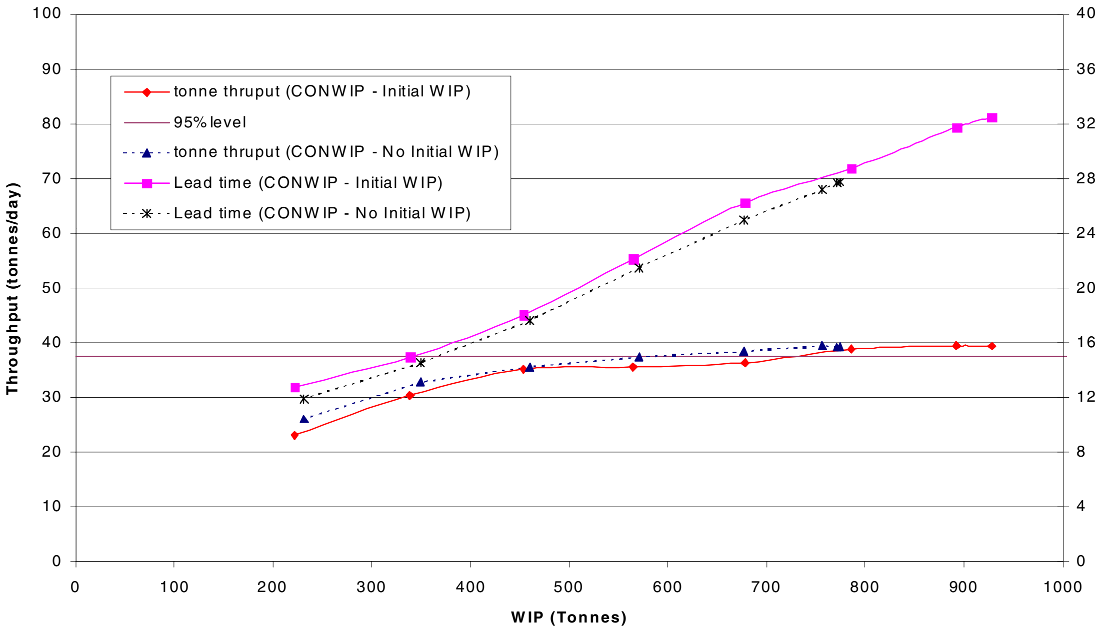

Figure 3: Tonne Throughput and Lead Time Versus Tonne WIP

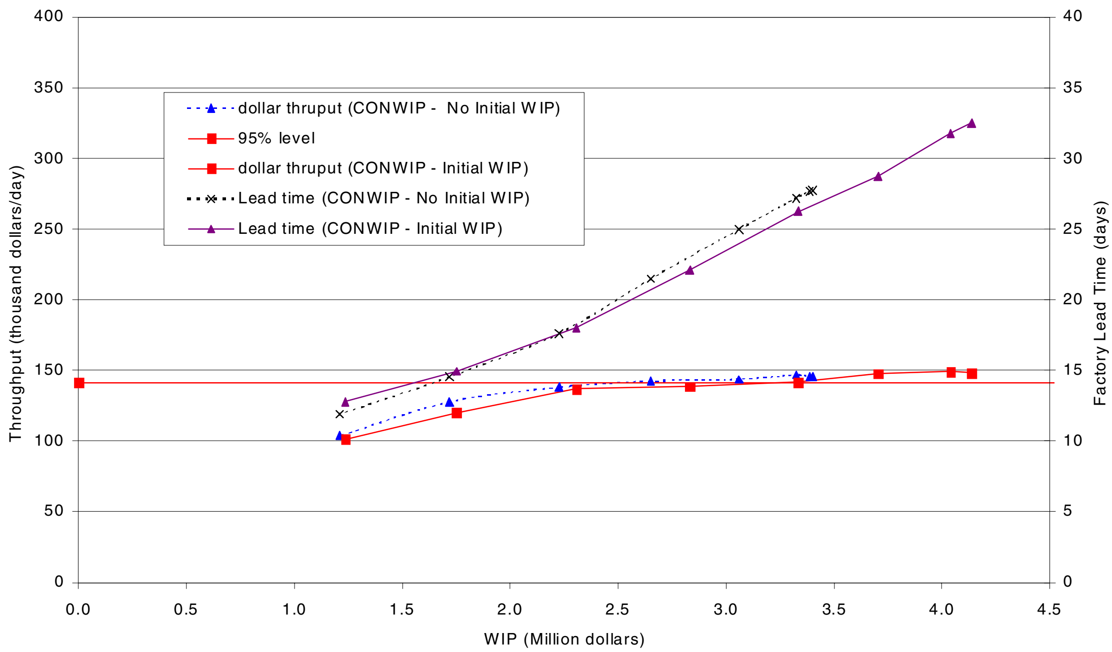

Figure 4: Dollar Throughput and Lead Time Versus Dollar WIP

levels. As the level of WIP drops, the factory lead time also drops. What this paper has suggested, however, is that the initial conditions in the model do matter, as a credible model of the facility could not be built without this initial inventory position. As the factory under investigation is an on-going concern, the WIP level is never zero, and the model must reflect this reality. Otherwise the results consistently underestimate the level of WIP and manufacturing lead times in the plant. Given this, the model results suggest a saving of $1.4 million in WIP, and 12 days lead time, can be obtained simply by capping the maximum level of WIP to around 1200 buckets for this plant.

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